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AUTOMOBILE EMISSIONS—CONTROL

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Picture for a moment any major industrialized city in the world on a hot summer day. Perhaps Los Angeles, Mexico City, or London come to mind. Few residents can ignore the ever-present signs of humankind that linger in the air, many of which are directly attributable to the internal-combustion engine and the automobile. Carbon monoxide (CO), hydrocarbons (HC), nitrogen oxides (NOx), fine particles, and lead are some of the compounds emitted by automobiles that foul the air.

See also AIR QUALITY MODELING. CLEAN AIR ACT. MOBILE SOURCES: ENVIRONMENTAL ANALYSIS.

In the United States, air pollution control measures to mitigate mobile emissions in nonattainment areas (as defined by the Clean Air Act) include inspection and mainte-
nance (I/M) programs, oxygenated fuel mandates, and transportation control measures. Nonetheless, many areas remain in nonattainment past the 1987 deadline for compliance with federal standards, and some are projected to remain in nonattainment for many more years despite the measures currently undertaken. A major emphasis in controlling mobile source emissions has centered around periodic testing for identifying vehicles with excessive emissions.

Current federal and state governments employ a variety of testing methods and protocols for certifying new and in-use vehicle emissions. These range from the extremely comprehensive new car certification test called the Federal Test Procedure, which all newly manufactured vehicles sold in the United States must comply with, to the more common one- or two-speed idle measurements performed in many state I/M programs (1–4). The former requires at least 12 h to complete and costs in excess of $700. The later requires less than 15 min and is priced around $10. Both tests are designed as surrogates for evaluating the emissions of vehicles under actual operating conditions. The limitations of each type of testing have been hotly debated. The following criteria have been outlined (5) for an “ideal” test: it should evaluate the vehicle under real-life conditions and be reproducible, accurate, quick, inexpensive, and measure all pollutants of concern.

In 1987, with support from the Colorado Office of Energy Conservation at the University of Denver developed an infrared (ir) remote-monitoring system for automobile carbon monoxide exhaust emissions (6). Significant fuel economy improvements result if rich-burning (high CO and HC emissions) or misfiring (high HC emissions) vehicles are tuned to a more stoichiometric and more efficient air:fuel (A:F) ratio. Therefore, the University of Denver CO–HC remote sensor is named the Fuel Efficiency Automobile Test (FEAT). The basic instrument measures the carbon monoxide:carbon dioxide ratio (CO:CO₂) and the hydrocarbon:carbon dioxide ratio (HC:CO₂) in the exhaust of any vehicle passing through an ir light beam that is transmitted across a single lane of roadway. Figure 1 shows a schematic diagram of the instrument (7).

**THEORY OF OPERATION**

The FEAT instrument was designed to emulate the results one would obtain using a conventional nondispersive infrared (NDIR) exhaust gas analyzer. Thus FEAT is also based on NDIR principles. An ir source sends a horizontal beam of radiation across a single traffic lane, approximately 0.25 m above the road surface. This beam is directed into the detector on the opposite side and divided between four individual detectors: CO, CO₂, HC, and a reference. An optical filter that transmits infrared light of a wavelength known to be uniquely absorbed by the molecule of interest is placed in front of each detector, determining its specificity. Reduction in the signal caused by absorption of light by the molecules of interest reduces the voltage output. One way of conceptualizing the instrument is to imagine a typical garage-type NDIR instrument in which the separation of the ir source and detector is increased from 0.08 to 6–12 m. Instead of pumping exhaust gas through a flow cell, a car now drives between the source and the detector.

Because the effective plume path length and amount of plume seen depends on turbulence and wind, the FEAT can only directly measure ratios of CO:CO₂ or HC:CO₂. These ratios are constant for a given exhaust plume and by themselves are useful parameters to describe the combustion system. However, with a fundamental knowledge of combustion chemistry, it is possible to determine many other parameters of the vehicle’s operating characteristics from these ratios, including the instantaneous air:fuel
ratio, grams of CO or HC emitted per liter of gasoline (g CO/L or g HC/L) burned, and the percent CO or percent HC in the exhaust gas. Most vehicles show ratios of zero, because they emit little to no CO or HC. To observe a CO:CO₂ ratio greater than zero, the engine must have a fuel-rich air:fuel ratio and the emission control system, if present, must not be fully operational. A high HC:CO₂ ratio can be associated with either fuel-rich or fuel-lean air:fuel ratios coupled with a missing or malfunctioning emission-control system. A lean air:fuel ratio, while impairing driveability, does not produce CO in the engine. If the air:fuel ratio is lean enough to induce misfire then a large amount of unburned fuel is present in the exhaust manifold. If the catalyst is absent or nonfunctional, then high HC will be observed in the exhaust without the presence of high CO. To the extent that the exhaust system of this misfiring vehicle contains some residual catalytic activity, the HC may be partially or totally converted to a CO:CO₂ mixture.

**INSTRUMENT DETAILS**

The present design of University of Denver FEAT instruments incorporates CO (4.6 μm), CO₂ (4.3 μm), HC (3.4 μm), and background (3.9 μm) channels using interference filters built into Peltier-cooled lead selenide detectors. The instrument uses a mirror to collect the light and focus it onto a spinning 12-faceted polygon mirror that provides a periodic detector illumination of 2400 Hz. The reflected light from each facet of the rotating mirror sweeps across a series of four focusing mirrors that in turn direct the light onto the four detectors as shown in Figure 2. Each detector thus gets a burst of full signal from the source in a sequential fashion for each measurement mode.

Each detector provides a pulse train at 2400 Hz equivalent to the intensity of the IR radiation detected at its specific wavelength. Electronic circuitry averages 24 of these pulses, subtracts any background signal, and provides the averaged DC level to four signal ports. These are connected to a computer through an analogue-to-digital converter. Figure 3 shows 0.5 s of zero-corrected exhaust data voltages from the HC, reference, CO, and CO₂ detectors. Voltage levels are monitored in front of and behind each passing vehicle to eliminate effects of variable background concentrations.

All data from the CO, CO₂, and HC channels (I) are corrected by ratio to the reference channel (I₀). This procedure eliminates other sources of opacity such as soot, turbulence, spray, license plates, etc from providing data that could be incorrectly identified as CO or HC. These reference-corrected values are then apportioned according to the detector-specific response factors and the resulting values for CO and HC are compared with CO₂ as shown in Figure 4. The resulting slope for CO:CO₂ (and HC:CO₂) is the path-independent measurement for that vehicle.

Software written for these instruments computes percent CO, percent CO₂, and percent HC on a dry, excess air-corrected basis from the measured CO:CO₂ and HC:CO₂ ratios. These reported values are designed to be equivalent to the percentages a standard garage analyzer would measure if one could run along behind the vehicle with a tailpipe probe. The percent HC is reported as an equivalent concentration of propane. This procedure is different from the reported HC measurements in most analyzers used in I/M programs. Most I/M instruments are tested for a single propane:hexane response ratio. All subsequent calibrations are performed with propane, yet the data are reported as “hexane equivalent” by dividing the measured number by the propane:hexane response ratio (a divisor usually close to two). The response factor for the FEAT is also close to two. Nevertheless, HC data...
Figure 4. The final CO:CO₂ correlation graph of the data in Figure 3 used to obtain a unitless slope. The HC:CO₂ ratio is determined via the same process.

are reported in propane units because the device is, in fact, calibrated daily with propane not hexane.

The FEAT can be accompanied by a video system to record license plates. The video camera is coupled directly into the data analysis computer so that the image of the back of each passing vehicle is frozen onto the video screen. The computer writes the date, time, and the calculated exhaust CO, HC, and CO₂ percentage concentra-

tions at the bottom of the image. These images are stored on videotape or digital storage media.

Before each day's operation in the field, a quality assurance calibration is performed on the instrument with the system set up in the field. A puff of gas designed to simulate all measured components of the exhaust is released into the instrument's path from a cylinder containing industry-certified amounts of CO, CO₂, and propane. The ratio readings from the instrument are compared with those certified by the cylinder manufacturer and used as a daily adjustment factor.

The FEAT is effective across traffic lanes of up to 15 m in width. It can be operated across double lanes of traffic with additional video hardware; however, the normal operating mode is on single-lane traffic (8). The FEAT operates most effectively on dry pavement, as rain, snow, and tire spray from a wet pavement scatter the IR beam. At suitable locations exhaust from more than 2,000 vehicles per hour can be monitored. The unit has been tested successfully for vehicle speeds exceeding 241 km/h. The FEAT has been used to measure the emissions of more than 750,000 vehicles worldwide. Table 1 compares the results for many of the locations that have been sampled (9–16).

The FEAT has been shown to give accurate readings for CO and HC in double-blind studies of vehicles both on the road and on dynamometers (17–19). A fully instrumented vehicle with tailpipe emissions controllable by the driver or passenger has been used in a series of drive-by experiments with the vehicles emissions set for CO between 0% and 10% and between 0% and 0.35% (propane) for HC to confirm the accuracy of the on-road readings.

Table 1. Worldwide Data Summary

<table>
<thead>
<tr>
<th>Location</th>
<th>Date</th>
<th>Number of Measurements</th>
<th>Mean Percent CO</th>
<th>Median Percent CO</th>
<th>Mean Percent HC</th>
<th>Median Percent HC</th>
</tr>
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<tr>
<td>United States</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Denver</td>
<td>1991–1992</td>
<td>35,945</td>
<td>0.74</td>
<td>0.11</td>
<td>0.057</td>
<td>0.033</td>
</tr>
<tr>
<td>Denver</td>
<td>1993</td>
<td>58,894</td>
<td>0.58</td>
<td>0.13</td>
<td>0.022</td>
<td>0.013</td>
</tr>
<tr>
<td>Chicago</td>
<td>1990</td>
<td>13,640</td>
<td>1.10</td>
<td>0.37</td>
<td>0.139</td>
<td>0.087</td>
</tr>
<tr>
<td>Chicago</td>
<td>1992</td>
<td>8,733</td>
<td>1.04</td>
<td>0.25</td>
<td>0.088</td>
<td>0.064</td>
</tr>
<tr>
<td>California</td>
<td>1991</td>
<td>91,679</td>
<td>0.82</td>
<td>0.14</td>
<td>0.076</td>
<td>0.042</td>
</tr>
<tr>
<td>Provo, Utah</td>
<td>1991–1992</td>
<td>12,066</td>
<td>1.17</td>
<td>0.45</td>
<td>0.220</td>
<td>0.127</td>
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<tr>
<td>El Paso, Tex.</td>
<td>1993</td>
<td>15,986</td>
<td>1.22</td>
<td>0.37</td>
<td>0.073</td>
<td>0.044</td>
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<td>Mexico</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Juarez</td>
<td>1993</td>
<td>7,640</td>
<td>2.96</td>
<td>2.18</td>
<td>0.170</td>
<td>0.091</td>
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<tr>
<td>Mexico City</td>
<td>1991</td>
<td>31,538</td>
<td>4.30</td>
<td>3.81</td>
<td>0.214</td>
<td>0.113</td>
</tr>
<tr>
<td>Europe</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Göteborg, Sweden</td>
<td>1991</td>
<td>10,285</td>
<td>0.71</td>
<td>0.14</td>
<td>0.058</td>
<td>0.046</td>
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<tr>
<td>Denmark</td>
<td>1992</td>
<td>9,038</td>
<td>1.71</td>
<td>0.67</td>
<td>0.177</td>
<td>0.058</td>
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<tr>
<td>Thessaloniki, Greece</td>
<td>1992</td>
<td>10,536</td>
<td>1.40</td>
<td>0.55</td>
<td>0.155</td>
<td>0.082</td>
</tr>
<tr>
<td>London, UK</td>
<td>1992</td>
<td>11,666</td>
<td>0.96</td>
<td>0.17</td>
<td>0.136</td>
<td>0.071</td>
</tr>
<tr>
<td>Leicester, UK</td>
<td>1992</td>
<td>4,992</td>
<td>2.32</td>
<td>1.61</td>
<td>0.212</td>
<td>0.131</td>
</tr>
<tr>
<td>Edinburgh, UK</td>
<td>1992</td>
<td>4,524</td>
<td>1.48</td>
<td>0.69</td>
<td>0.129</td>
<td>0.084</td>
</tr>
<tr>
<td>Asia</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bangkok, Thailand</td>
<td>1993</td>
<td>5,260</td>
<td>3.04</td>
<td>2.54</td>
<td>0.948</td>
<td>0.567</td>
</tr>
<tr>
<td>Hong Kong</td>
<td>1993</td>
<td>5,891</td>
<td>0.96</td>
<td>0.18</td>
<td>0.054</td>
<td>0.037</td>
</tr>
<tr>
<td>Kathmandu, Nepal</td>
<td>1993</td>
<td>11,227</td>
<td>3.85</td>
<td>3.69</td>
<td>0.757</td>
<td>0.363</td>
</tr>
<tr>
<td>Seoul, Korea</td>
<td>1993</td>
<td>3,104</td>
<td>0.82</td>
<td>0.26</td>
<td>0.044</td>
<td>0.019</td>
</tr>
<tr>
<td>Taipei, Taiwan</td>
<td>1993</td>
<td>12,062</td>
<td>1.49</td>
<td>0.88</td>
<td>0.062</td>
<td>0.050</td>
</tr>
<tr>
<td>Australia</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Melbourne</td>
<td>1992</td>
<td>15,908</td>
<td>1.42</td>
<td>0.57</td>
<td>0.107</td>
<td>0.058</td>
</tr>
</tbody>
</table>
The comparison between the on-board measurements and the FEAT measurements is shown in Figure 5. The results have an accuracy of ± 5% for CO and ± 15% for HC. Recently, the abilities to measure nitric oxide and exhaust opacity have been added. NO is measured by ultraviolet absorption, whereas opacity is determined by means of IR absorption at 3.9 µm. Diesel soot (black) and so called “steam” from cold cars both cause observable opacity. Current units measure visible steam as HC. A system to eliminate this interference is under development.

REAL-WORLD VEHICLE EMISSION CHARACTERISTICS

Through the use of FEAT it is now possible to collect data quickly and easily on a large number of vehicles. This enables the study of important questions concerning the automobile’s contribution to urban air quality and what mitigation actions might be taken. Following is a brief overview of general characteristics about automobile emissions that have been determined so far through the use of FEAT. Several interesting data sets have been collected that highlight the usefulness of large real-world databases.

Not all cars have equal emissions. Data show that a small fraction of the passing vehicles is responsible for half or more of the emissions in any given area. In Denver half the emissions come from only 7% of the vehicles. In Kathmandu half the emissions come from 25% of the vehicles. Figure 6 shows data collected at a single site in the Los Angeles area. At this location half of the CO is emitted by 7% of the vehicles and half of the HC is emitted by 11% of the vehicles. The few vehicles emitting half of the CO and HC are referred to as gross polluters. For automobile emissions the old adage “the tail wags the dog” holds true.

The overall characteristics of these fleets are similar regardless of age, location, or the presence or absence of I/M programs and can be mathematically described by a γ distribution (21). Most vehicles show mean emissions of 1% CO and 0.1% HC (as propane) or less in the exhaust.
The newer the fleet the more skewed the emissions. This is because more of the vehicles have near zero emissions, and thus a smaller number of gross polluters dominates the total emissions.

The good news is that for the U.S. fleet 50% of the vehicles produce only 4% of the CO emissions and 16% of HC, using current gasoline formulas as fuel. This shows that alternative and reformulated fuels are not likely to solve a problem that apparently arises due to a lack of maintenance.

Not all gross polluters are old vehicles (only about 25% of pre-1975 vehicles in the United States). In fact, even the majority of precatalyst vehicles emit relatively low levels. There is a strong correlation between fleet age and fleet emissions (Fig. 7a). However, this correlation has less to do with emissions-control technology than it does with vehicle maintenance. Any well-maintained vehicle regardless of age can be relatively low emitting, as seen by the mean emissions for all model years in the lowest-emitting quintile. It can also be seen that the most rapid deterioration in emissions occurs during the first 11 yr of ownership. It is interesting to note that the vehicles with the most rapidly deteriorating emissions are all newer technology vehicles with computer-controlled fuel delivery systems and three-way catalysts (installed in the United States after 1982). All of the studies note that these vehicles have negligible emissions when first purchased, emphasizing the need for proper maintenance.

If the problem is not the old clunker, then which vehicles are responsible? The product of the average emissions (Fig. 7a) and the fleet distribution (Fig. 7b) shown in Figure 7c, represents the overall contribution for each model year. What is obvious is that although older vehicles (pre-1980) have higher average emissions, it is the newer and more prevalent (post-1980) vehicles that actually contribute the most to the total. This has important implications for regulatory agencies that design programs around vehicle age only.

For HC, the fleet emissions tend to be less skewed than for CO, with a larger percentage of vehicles responsible for the majority of the fleet emissions. Only four cities (Bangkok, Hong Kong, Kathmandu, and Taipei) have half of the HC emissions produced by more than 15% of the fleet. Most of the same conclusions that are drawn regarding CO emissions and fleet characteristics hold true for HC emissions, because HC emissions increase as engine combustion gets richer and produces more CO. Two cities in Asia (Bangkok and Kathmandu) stand out for HC emissions, in large part due to the high percentage of two-cycle engines (necessarily high HC emitters by design).
many of which also appear to be poorly tuned and maintained.

REMOTE SENSING APPLICATIONS

The ability quickly and unobtrusively to monitor real vehicles under real conditions opens up the possibility for many new applications. The ideas have run the gamut from pure research on emissions and control equipment performance to using the measurements as a basis for emission pricing schemes (by which the toll or vehicle registration is prorated according to the emission level). In the following section, data from several research programs that have used FEAT and the potential implications and logical extensions of that data to emission-control programs are addressed.

Roadside Pullover Studies

The ability of FEAT to identify gross polluters has been tested in several pilot studies. Two such programs in California have sought out explanations for vehicles with excessive emissions. In both studies, FEAT was used to identify gross polluting vehicles. A police officer stops the vehicle and performs a roadside inspection of the vehicle's tailpipe emissions and emission-control equipment status. In California, this type of inspection is called a smog check and is required once every 2 yr for gasoline-powered vehicles registered in most parts of the state.

The first California study involved the nonrandom inspection of 60 vehicles, 50 of which were stopped for having FEAT readings of greater than 2% CO (17). What was discovered was that of the 50 vehicles stopped for elevated CO emissions 45 failed the roadside inspection. One of the chief reasons for the high failure rate was that 12 of the 45 vehicles were found to have tampered emissions-control equipment. This means that emission-control equipment that was originally on the vehicle had been removed or otherwise disabled. The most glaring example was a 1984 GMC pickup that was originally purchased equipped with a diesel engine but was found to have a gasoline engine without any required emissions-control equipment. Because this vehicle was still registered as a diesel-powered vehicle, it was exempt from the biannual state inspection program.

To verify these results on a larger sampling of vehicles, an expanded pullover program was conducted during June 1991 in a suburb of Los Angeles (13). Following a similar protocol, vehicles were selected nonrandomly based on a 4% CO or 0.4% HC on-road emissions level. Two inspection teams conducted roadside inspections of the vehicles that were stopped. In 2 weeks of measurements 60,487 measurements on 58,063 vehicles were performed. In all 3,271 gross polluting vehicles were identified, from which 307 vehicles were stopped and inspected. In the roadside inspection, 92% failed, with tampered emissions control equipment again a leading reason. A total of 41% of the vehicles were found out of compliance and an additional 25% had defective emissions-control equipment that may not have been caused by intentional tampering. The tailpipe portion of the test had an 85% failure rate.

These data strongly suggest that excessive tailpipe emissions are often the result of vehicles with broken or defective emissions-control equipment. This undoubtedly has been influenced by the willful tampering that has taken place in a large number of the examples. It is also apparent that the scheduled testing program that California has depended on to find these tampered vehicles is being circumvented by the public. The classic example of this is the case of the diesel to gasoline engine switch mentioned previously (an additional case was found in the second pullover study). Aggressive antitampering programs using FEAT as probable cause for a pullover inspection could begin quickly and effectively to address another segment of the excessive mobile source tailpipe emissions.

Provo Pollution Prevention Program

In a study conducted in Provo, Utah, gross polluting vehicles were recruited from the public through FEAT measurements to investigate repair costs and effectiveness (22). Provo was chosen because it is an area that regularly violates the national ambient CO standard during the winter months. Measurements were made at two off-ramps (one northbound and one southbound) from I-15 at the entrance to Provo during November 1991 and January 1992 in search of vehicles that exceeded a 4% CO emission level on at least two occasions. Two ramps were used to impose a control on the study, ie, vehicles were only recruited from one of the two ramps. In this way it was possible convincingly to compare emission changes at one ramp with those at the companion ramp as a judge of overall repair effectiveness. At these locations it was observed that half of the CO emissions were being produced by only 9% of the vehicles. For the entire program 17,000 measurements of more than 10,000 individual vehicles were made.

With the help of the city and a local community college, 47 out of 114 identified vehicles were recruited with the promise of a rental vehicle and free emission-related repairs. All of the work was carried out by local repair shops with the community college overseeing that the work paid for was in fact performed. Repairs ranged from the simple, such as fixing automatic chokes, to the extensive repair of replacing a cam shaft, lifters, and timing chain. In all, repairs for the 47 vehicles averaged $195 with an additional $43/vehicle spent on providing rental cars. In April 1992, through more on-road emission measurements, the effectiveness of the diagnosis and repairs at reducing CO emissions from these 47 vehicles was evaluated.

Table 2 shows, by model year, the 28 vehicles that were successfully remeasured. On average, the repairs resulted in a 50% reduction in the observed on-road emissions, with 25 of the remeasured vehicles showing statistically significant CO emission reductions. The remaining three vehicles were measured to have statistically the same or increased CO emission when compared with the before-repair measurements. These repair reductions were also found to be statistically significant when compared with the control group of vehicles that were identified from the control ramp but not included in the repair program.

In terms of the cost effectiveness of the repairs, it was estimated that CO was reduced from the 47 vehicles for approximately $181/t. This compares favorably with an
Table 2. Repair Data Summary According to Vehicle Emissions Technology Grouping for the 28 Vehicles that Were Successfully Remeasured after Repairs

<table>
<thead>
<tr>
<th>Model Year Grouping</th>
<th>Number of Vehicles</th>
<th>Average g CO/L before Repairs</th>
<th>Average g CO/L after Repairs</th>
<th>Average g CO/L Reduction</th>
<th>Average g CO/L for Provo Fleet</th>
</tr>
</thead>
<tbody>
<tr>
<td>post-1982</td>
<td>6</td>
<td>5931</td>
<td>2540</td>
<td>3391</td>
<td>867</td>
</tr>
<tr>
<td>1981–1982</td>
<td>1</td>
<td>5821</td>
<td>2305</td>
<td>3516</td>
<td>1911</td>
</tr>
<tr>
<td>1975–1980</td>
<td>16</td>
<td>5314</td>
<td>2702</td>
<td>2612</td>
<td>2589</td>
</tr>
<tr>
<td>pre-1975</td>
<td>5</td>
<td>6662</td>
<td>4285</td>
<td>2377</td>
<td>4012</td>
</tr>
</tbody>
</table>

estimate for I/M programs of $708/t (23), oxygenated fuel programs of $0 to $1147/t (9,23,24), and of $930/t for an old vehicle scrappage program (25). A major advantage of this approach is the ability to measure directly the program's effectiveness, allowing alterations and adjustments to be made to improve the results further.

Swedish Vehicle Study

In the 1991 data from Los Angeles, the European nạmeplate vehicles tend to have the lowest emissions. It was speculated that this is because they are well maintained. Data from the California Air Resources Board (CARB) listing manufacturer-specific failure rates for smog check reinforces this perception (26). The CARB data show Saab and Volvo with the lowest and third lowest smog check failure rates, respectively.

In September 1991, a study was conducted in Göteborg, Sweden (14). The location was a freeway interchange ramp (Gullbergsommet) just across the river from the Volvo factory and downriver from the Saab manufacturing facility. In the Swedish study, emissions from 4011 Saabs and Volvos were measured. Sweden has a stringent I/M program (fail badly and the vehicle is towed to a repair shop). Sweden mandated closed-loop catalytically controlled systems in 1988. They were phased in during the 1987 model year, with about 50% of the vehicles. The 1986 and older Saabs and Volvos in Sweden are not equipped with any type of catalytic converter.

The data from Sweden (4011 vehicles) and Los Angeles (536 vehicles) were used to examine the effects of technology and maintenance on vehicle emissions. By comparing these presumably well-maintained high technology vehicles to the well-maintained lower technology Swedish vehicles, the effects of technology ought to be readily observable. Figure 8 shows the emission data for CO and HC. For 1978–1986 model years, the CO and HC emissions of the Los Angeles vehicles average about 0.4% and 0.04%, respectively. For the Swedish vehicles of the same model years, the CO and HC emissions average about 1.5% and 0.06%, respectively. The improved technology of the Los Angeles fleet of Saabs and Volvos has clearly resulted in lower emissions, even for older vehicles. For 1988 model years and newer, when both fleets incorporated the same technology, the Swedish vehicles in Los Angeles and Göteborg are indistinguishable.

The dramatic drop in average vehicle emissions in Sweden following the 1987–1988 introduction of catalysts is only barely discernable in the first three quintiles of the California database (Fig. 7a), because catalysts were introduced longer ago. In Melbourne, Australia, catalysts were introduced in 1986. The dramatic improvement shown in Swedish vehicles also is not observed in the 15,908 vehicle Australian database. It was suspected that

Figure 8. (a) Average percent CO for Saabs and Volvos measured in Los Angeles (LA) during the summer of 1991 compared with the same model year vehicles measured in Göteborg, Sweden (SW), during September of the same year. (b) Average percent HC for Saabs and Volvos measured in the same study.
Australian maintenance is more like California and less like Sweden.

To examine further the effect of maintenance on emissions, emissions from the Los Angeles fleet of 1978–1986 model year U.S. vehicles were compared with the same model year noncatalyst vehicles in Sweden. The Swedish vehicles averaged 1.5% CO and 0.08% HC. The emissions of U.S. vehicles were slightly lower for CO and comparable for HC. In other words, the well-maintained Swedish noncatalyst vehicles emit nearly the same CO and HC as the overall (less well-maintained) U.S. fleet in Los Angeles. This demonstrates that a high level of maintenance is as important as technology to the higher emitting (on average) older model year vehicles.

Finally, emissions from Saabs and Volvos in Los Angeles are higher in the pre-1976 fleet than in the Swedish fleet. Because vehicles rust faster in Sweden, the pre-1976 fleet is much older, on average, in Los Angeles. The older Saabs have two-stroke engines, which are notorious for HC emissions and often tuned to produce high CO; thus it is not surprising that the older fleet in Los Angeles has higher average emissions.

Swedish-manufactured vehicles appear to be well maintained in both Sweden and Los Angeles. In both locations, they have used computer-controlled port fuel injection for more than 20 yr. In Los Angeles, these vehicles also have used catalysts since 1960, whereas in Sweden, catalysts were not introduced until 1987. These data have been used to conduct two thought experiments in which the citizens of Los Angeles are imagined to all drive Swedish nameplate vehicles. The first assumes that all vehicles are constructed, operated, and maintained as in Los Angeles (ie, their emissions match the entire California fleet for all makes). The second assumes they are constructed, operated, and maintained as in Sweden. The overall emissions of the vehicle fleet measured in California in the 1991 study averaged 0.79% CO and 0.076% HC. The same age distribution as this overall fleet but with the emissions distribution of the Swedish-manufactured vehicles currently in use in Los Angeles gives average CO and HC emissions of 0.49% and 0.056%, respectively. The same age distribution but with the emissions of the Swedish-manufactured vehicles currently in use in Sweden gives average CO and HC emissions of 0.9% and 0.066%, respectively. The better maintenance with catalytic control provides a reduction of 38% and 26% for CO and HC, respectively. The better maintenance alone provides an increase of 14% for CO and a reduction of 13% for HC. It was concluded that better maintenance of the current fleet in Los Angeles could provide on-road emissions reductions greater than 25% for both CO and HC. To the extent that remote sensing offers lower cost emissions testing, the money saved could be spent on more important diagnosis and repair functions.

CONCLUSIONS

On-road remote sensing can now be used to analyze the emissions of a large fleet of vehicles in a cost-effective manner without inconveniencing the driving public. The statistics of the data can be used to plan and evaluate emission-control programs. The identification of gross polluters can be used as a component of a program designed to ensure that those vehicles receive effective repair (an inspection and maintenance program). Excessive on-road readings have been used as evidence for pulling vehicles over to the side of the road to check for tampering with the emissions-control system finding a high incidence of such behavior.

Remote sensing can be applied at the same site under the same conditions periodically to determine how well efforts are working to reduce on-road emissions. Because the correlation between low emissions and proper maintenance is high, most people operate vehicles that do not contribute significantly to pollution. These people could be rewarded for their socially responsible behavior based on low on-road emissions readings. On-road remote sensing of motor vehicle emissions is a new tool that has progressed from a university prototype to a commercially available system, which is either portable or mounted in a mobile van. Everywhere the system has been tried, local air pollution officials have suggested new ways in which this tool could be applied to solving their mobile source emissions problems.

BIBLIOGRAPHY

Automotive engines are those power plants used to propel both highway and off-highway vehicles. Essentially all these power plants are reciprocating internal combustion engines of one of two types: spark-ignition engines or diesel engines. In either type, a piston reciprocates within a close-fitting cylinder. This reciprocating linear motion is transformed into continuous rotation of a crankshaft by means of a connecting rod that is pinned to the piston and crankshaft. Once each engine cycle, the piston compresses a quantity of air (or air-fuel mixture). The fuel in the gas is ignited and burned when the piston has compressed the gas to its minimum volume, and the heat produced by combustion raises the temperature and pressure of the mixture. The subsequent motion of the piston expands the hot, high-pressure gases and extracts work from the gas mixture, which is used to rotate the crankshaft and through various types of power transmission devices, propel the vehicle. The expanded gas mixture is then released to the surrounding atmosphere and the cylinder is filled with a fresh charge. Fuels most commonly used for automotive engines are mixtures of various hydrocarbon compounds refined from crude petroleum. Gasolines having a relatively high vapor pressure and a high autoignition temperature are used in spark-ignition engines; diesel fuels having lower vapor pressures and autoignition temperatures are used in diesel engines. The products of combustion from such fuels are principally nitrogen (from the air), carbon dioxide, and water vapor. The exhaust gases may also contain smaller percentages of carbon monoxide, unburned or partially-burned hydrocarbons, nitrogen oxides, and particulate matter consisting mostly of carbon (soot). The quantity of these latter materials are regulated by law in most of the nations of the world, since these emissions contribute significantly to atmospheric pollution. In addition, it is hypothesized that carbon dioxide in the atmosphere creates a "greenhouse" effect that may eventually result in global warming, although no legal restrictions have yet been placed on the quantity of carbon dioxide produced. The development of methods to reduce harmful emissions from automotive engines is undoubtedly the most pressing concern of engine designers and manufacturers.

See also Methanol Vehicles; Supercars; Exhaust Control; Automotive; Transportation Fuels; Automotive Fuels; Knock; Gum in Gasoline; Internal Combustion Engine.

ENGINE TYPES AND ARRANGEMENTS

The Four-Stroke Cycle

The four-stroke cycle, as its name implies, requires four strokes of the piston to complete one cycle. An engine using this cycle has intake and exhaust valves in the cylinder head (see Fig. 1). During the intake stroke, the intake valve is open and the piston moves downward, drawing into the cylinder a charge of air and fuel. As the piston reaches the end of its downward stroke, the intake valve closes. During the subsequent upward stroke, the fuel-air mixture is compressed (without significant heat transfer to or from the charge, or "isentropically"). At the end of this compression stroke, the fuel-air mixture is ignited (by a spark, for instance) and burnt. The exothermic reaction produced by oxidation of the fuel increases the pressure and temperature of the gases in the cylinder. During the next downward stroke the hot, high pressure gases are expanded. At the end of the expansion stroke, the exhaust valve opens and during the next upward stroke the gases are exhausted to the atmosphere.

The four strokes of the cycle (intake, compression, expansion, exhaust) are repeated continuously to produce a continuous rotation of the crankshaft. The piston produces a quantity of work during the expansion stroke that is greater than that required for the other three strokes, the friction of the engine, and for the operation of accessories (e.g., alternators, fuel pumps, water pumps, fans). The net work is applied to the crankshaft and provides the energy needed to propel the vehicle.

Figure 1 also shows the various events of the cycle plotted on a pressure–volume chart. The compression stroke traces out the curve 1–2. Combustion (2–3) raises the pressure at constant volume. Expansion (3–4) is terminated by a sharp drop in pressure (4–5) as the exhaust valve opens. At the end of the exhaust stroke (5–6), the exhaust valve closes and the intake valve opens. As the piston begins to move downward, the pressure in the cylinder falls to the intake pressure (6–7), followed by the intake stroke (7–1).